Programme Area: Energy Storage and Distribution

Project: 2050 EIO Multi Vector Integration Analysis

Title: Multi Vector Interactions Report

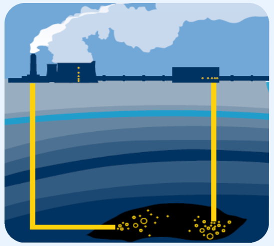
Abstract:

The report provides an initial assessment of potential interactions across energy vectors.

Context:

The project aims to improve the understanding of the opportunity for and implications of moving to more integrated multi vector energy networks in the future. Future energy systems could use infrastructure very differently to how they are employed today. Several individual energy vectors - electricity, gas and hydrogen - are capable of delivering multiple services and there are other services that can be met or delivered by more than one vector or network.





Multi-vector Integration Project

D1.1 - Report on multi-vector interactions and priority interactions shortlist

July 8th 2016

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Introduction

Introduction

- This document is submitted as Deliverable 1.1 under the ETI's Multi-vector Integration Project
- The material is adapted from the presentation provided to the project steering group at the 'Alignment Workshop' held in London on June 24th 2016
- The long-list of multi-vector interactions and the proposed filtering for further analysis in Work Package 2 were validated by the steering group during a follow up teleconference on July 4th 2016, and this document reflects this validated set of interactions

Structure of this document

- This document is structured as follows
  - Description of the methodology used to map and classify multi-vector interactions
  - An initial assessment of each case, describing the system, the issues addressed, the current situation and the likely 'materiality' for the UK energy system
  - The process used to filter and prioritise the cases, and the agreed shortlist
  - A recap of the subsequent work to be undertaken in Work Packages 2 and 3

A systematic approach was used to identify potential multi-vector interactions in the UK energy system

Methodology for identifying multi-vector interactions

- Project team explored systematically the system ‘services’ that could be provided by each energy vector
- Vectors considered were electricity, gas, hydrogen, district heating, liquid fuels
- Services considered were peak avoidance, flexibility using multiple vectors to supply the same load, overcoming a generation capacity constraint, avoiding curtailment of a generation asset, and backing up an energy source (see next slide)
- Classification according to these 5 services proved easier than considering only 3 levels of ‘end-use’, ‘local distribution’ and ‘generation’ as originally proposed by the project team, since the additional granularity allows a more robust assessment of the ‘diversity’ of multi-vector interactions being considered in terms of coverage of multiple vectors and services
- This service classification is consistent with the examples of multi-vector interactions given in the Request for Proposals i.e. one network providing peak capacity support for another; one network meeting the shortfall of another; two (or more) networks permanently working in tandem with one another; or where one vector is used to produce energy for another

Each multi-vector interaction has been classified on the basis of the service provided a first-cut view on materiality

Classification of service provided

Each multi-vector case can be classified by the type of service provided. The over-arching service types can be described as:

- **Peak avoidance** – *Mainly related to the electricity network. Electricity demand is substituted by another vector at peak times*
- **Flexibility** – *System provides ability to flex between vectors due to a range of price signals or constraints*
- **Generation capacity constraint** – *Switch from electricity to a different vector due to constrained generation capacity*
- **Generation curtailment** – *Curtailment of a generating technology due to network constraint or generation surplus*
- **Back-up** – *Use of an alternative energy vector to back-up a primary source*

The main type of service provided by each multi-vector case is identified by the tags on the right.

Peak

Flexibility

Capacity

Curtailment

Back-up

First glance view on materiality

The multi-vector case descriptions include a first-cut analysis of materiality, captured by the following RAG rating.

Low **Moderate** **High**

Less likely to be material → More likely to be material

An initial identification of multi-vector interactions was carried out based on the energy vector and the service(s) provided

Vector	Peak avoidance	Flexibility	Generation capacity constraint	Generation curtailment	Back-up
Electricity				Renewable electricity to hydrogen	
Gas	Gas CHP; switching industrial process heat to gas at times of electricity grid stress	Heat pumps with gas peak boilers	Gas CHP incl. excess electricity to heat pumps; AD to CHP	Anaerobic digestion to gas injection	
District heating	CHP with heat pumps in DH/single dwellings	CHP with heat pumps in DH/single dwellings	CHP with heat pumps in DH		
Hydrogen	Fuel cell PHEVs/RE-EVs switching to H2	H2 from pre-combustion CCS to power/transport/ heat; fuel cell PHEVs/RE-EVs; H2 from SMR and electrolysis	Fuel cell PHEVs switching to H2	Renewable hydrogen to grid injection, methanation, transport	Fuel cell vehicle to grid
Liquid fuels		PHEV fuel switching to petrol	PHEV fuel switching to petrol		PHEV vehicle to grid Back up oil heating

This initial mapping yielded the following 'long-list' of multi-vector interactions

The following multi-vector interactions or energy substitution options have been identified

- Heat pumps with peak load boilers
- CHP combined with a heat pump in a single building
- Non electric generation serving a district heating system
- Substitution of electric process heating with gas / liquid fuel technology
- Fuel cell vehicle feeding electricity to the home
- PHEV switching to liq. fuel only running during high electricity price period
- PHEV displacing electrical demand with petrol, including (V2G)
- Range extender H2FC vehicle – H2 to recharge batteries at times of electrical system stress
- RES-to-Gas (H2, CH4) or DH
- AD/Gasification to CHP or Grid Injection
- H2 from SMR or electrolysis into H2 grid
- H2 from pre-combustion CCS to power/transport/heat

Agreement at Alignment Workshop and follow up teleconference that this list represented a comprehensive list of multi-vector interactions, especially once sub-cases within each options are considered

A common format has been used to summarise the key features of each interaction

Capacity

Multi-vector system description

- *Description of the multi vector interaction, the associated technological and infrastructure requirements.*
- *Scale and likely locations for implementation.*

Issues addressed

- *Problems addressed by the multi-vector system.*
- *Solutions available under this solution.*
- *Projections relevant to determining the materiality of the system.*

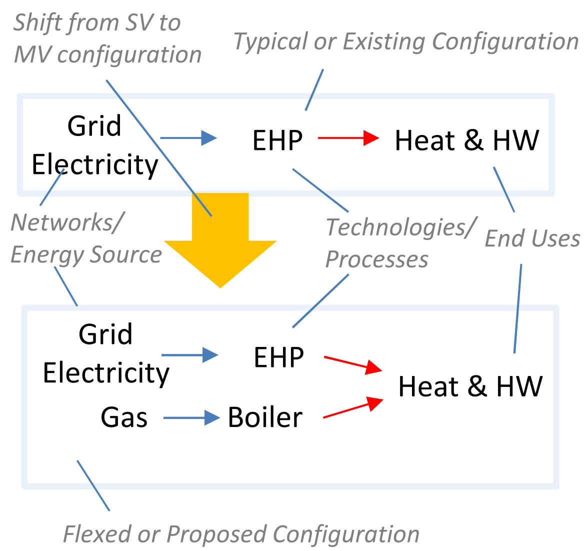
Current Situation

- *Brief description of current technological and infrastructure situation, outlook for the multi vector solution out to 2050.*

Materiality in UK energy system

- *Estimate of value unlocked and/or energy demand that can be managed using the multi vector solution against the counterfactual baseline.*

Process Flow Diagram and Key



Description of scenario under which this multi-vector solution would be significant.

Description of counterfactual baseline against which the multi vector solution will be assessed.

Electric heat pumps with gas boilers to meet peak heat demand in individual buildings

Peak

Multi-vector system description

> Electric heat pumps provide baseload heating demand with gas boilers used to meet peak heating demands or at times of electrical system stress.
> End-use technologies could be separate EHP and gas boiler or hybrid heat pump.

Issues addressed

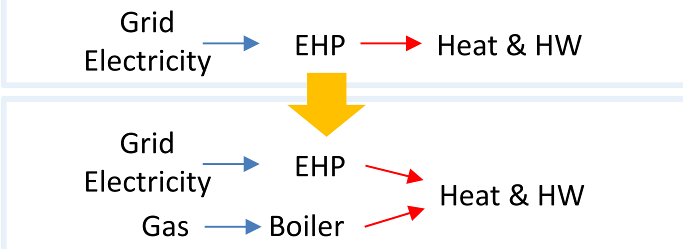
> Limits peak demands imposed on the electricity system, while still enabling a large fraction of heat demand to be electrified.
> Reduces investment required in electricity network reinforcement and peak generating capacity, but would require continued maintenance of gas network.

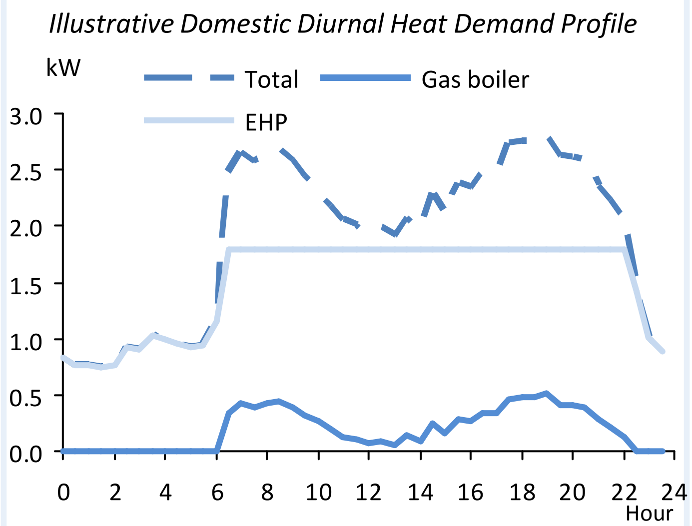
Current Situation

> The UK HP market at the moment is small, with the RHI encouraging few sales.
> Typically individual building heat pump installations replace gas boilers, given the £75 – 150 annual cost of gas network connection and the low marginal grid impact.

Materiality in UK energy system

> Smart Grid Forum's bullish scenarios forecast peak electricity demand increases of 20GW in 2030 and 40 GW in 2050 associated with deployment of approximately 6m and 12.5m HPs respectively.
> SGF estimate around £5bn value of grid reinforcements and upgrades to meet this capacity, before generation costs are even considered.
> Analysis of typical peak day profiles suggests 50% reduction in peak electricity load is possible at >75% heat demand met by EHP – corresponding to a potential 10GW capacity reduction in 2030[1].
> Gas network repex and opex are also significant; NG spending around £100m/year on their network (around 60% on HDPE switching and 40% maintenance)[2].





> Relevant under post-2020 scenarios for EHP uptake, locally relevant earlier in areas of network constraint

> Counterfactual is similar large scale electrification of heat and concurrent phase out of gas.

1. Based on SGF scenarios
2. *NGN 2012 Business Plan*

CHP combined with a heat pump in a single building

Peak

Multi-vector system description

- Gas CHP, in heat led mode, can be used to meet building heat demands, and the generated electricity can be used for building loads, or to power a heat pump. CHP heat can be used to improve the HP thermal performance, and a CHP-HP system can be flexed to match (high) building heat to power ratios.

Issues addressed

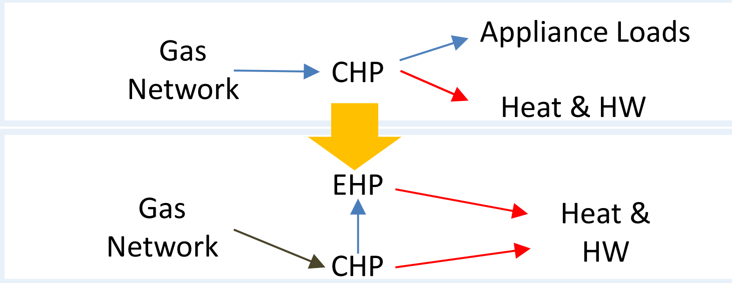
- Heat led CHP allows electrical loads to be taken off the grid, particularly at times of high thermal demand which are likely to coincide with LV peak demand.
- Potentially allows ultra high efficiency gas heating, with CHP electrical efficiencies of 25-30% (or higher in the case of fuel cell CHP) and heat pumps COPs of around 3. The environmental case for gas CHP will become weaker as grid decarbonises.

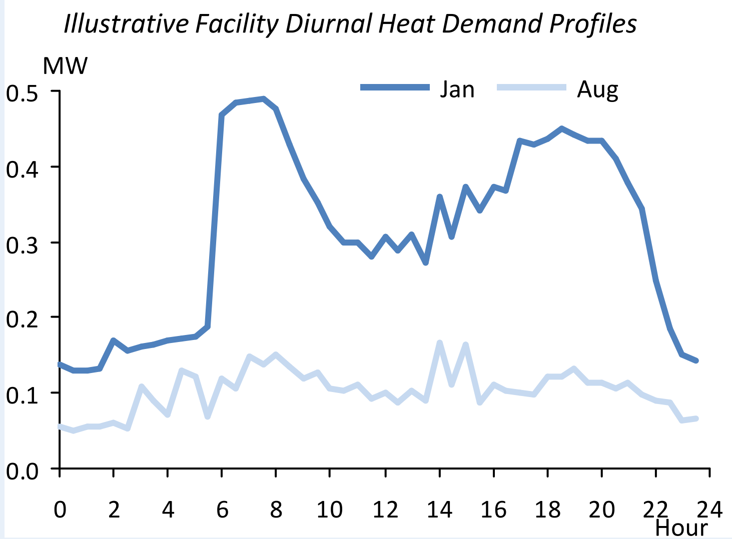
Current Situation

- Around 1,488 buildings in the UK use CHP, including universities (90), hotels (257) and leisure centres (478), though the number of schemes has not increased significantly since 2012. These represent a total of around 0.5GW.

Materiality in UK energy system

- Only likely to be relevant in buildings with high heat demand .
- Cost of two heating systems – unlikely to be attractive in building sector
- The environmental case for gas CHP will weaken as the grid decarbonises; by 2040 gas CHP heat will be 6 times[1] more carbon intensive than HP, even allowing for the emissions offset by the electrical generation.



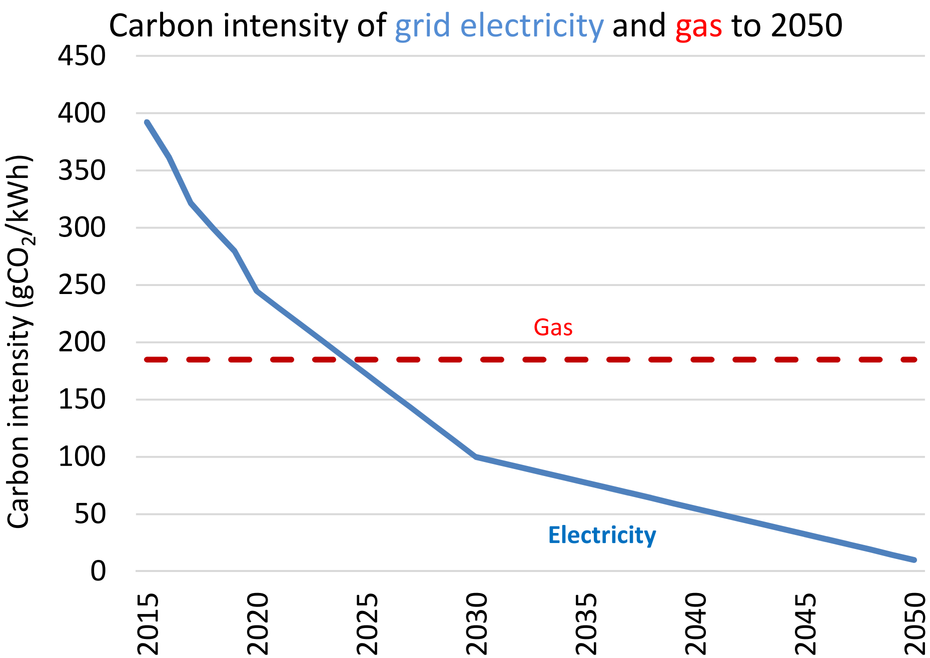


- Relevant in buildings with high heat demand and where CHP electricity would otherwise be exported to the grid.
- Counterfactual is increased electricity network & generating capacity to meet large scale electrification of heat.

1: Assumes thermal and electrical efficiencies of 60% and 25%, and HP COP of 3.

CHP combined with a heat pump in a single building

Factor	Estimate	Source
Size of existing and projected building CHP fleet.	Existing data taken from DUKES data, shown in table below.	*DUKES Chapter 7 Combined Heat and Power*
Relative carbon intensities of gas CHP and heat-pumps.	Fuel emissions per kWh shown below.	*DECC Energy and emissions projections*



UK Building Scale CHP Schemes

Sector	Number of schemes	Electrical Capacity MW(e)	Thermal Capacity MW(h)
Leisure	478	64	109
Hotels	257	37	62
Health	207	170	935
Residential Group Heating	98	48	110
Universities	90	89	474
Offices	39	15	19
Education	59	15	50
Government Estate	31	14	48
Retail	226	46	73
Other	3	0.7	1.1
Total	**1,488**	**498**	**1,881**

Gas CHP serving a district heating system and supplying power to heat pumps inside or outside the DH scheme at times of peak thermal demand

Peak

Multi-vector system description

- Around 80TWh of DH may be supplied in the UK by 2050. CHP and HP working in tandem allow such a scheme to flex their heat-to-power ratio and take advantage of peaks and troughs in electrical prices.

Issues addressed

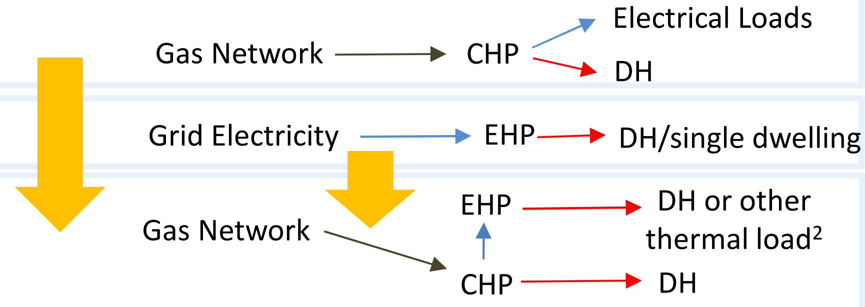
- HP/DH roll-out in areas of electricity grid constraint. Potential to switch between electricity and gas (or other fuel) in response to price signals.

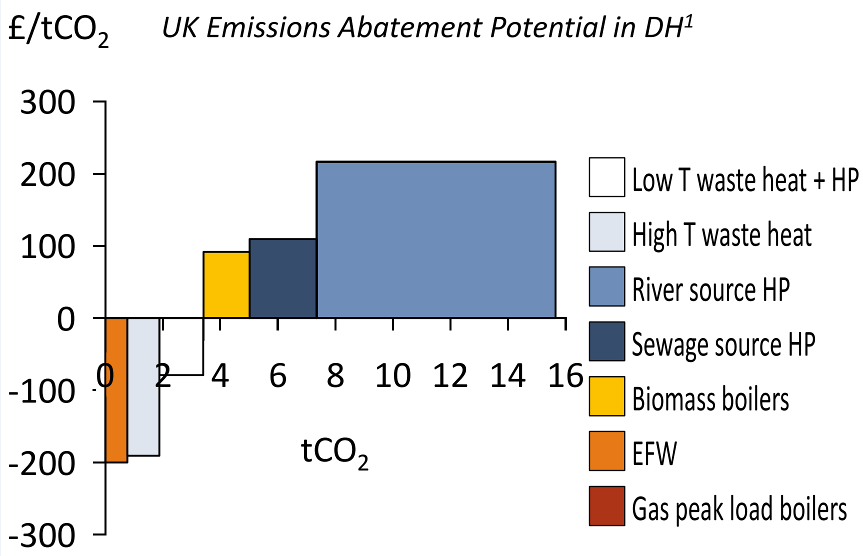
Current Situation

- In 2015, DH schemes in the UK provided around 5.6TWh[1] of heating, powered by a combination of waste heat and EfW and gas CHP, (very little of it using heat pumps).
- In Scandinavia, hybrid CHP and HP DH systems are used.

Materiality in UK energy system

- Heat pumps are projected[1] to supply around 11TWh of DH by 2030 and 53TWh by 2050, drawing 4TWh and 18TWh of electricity.
- For a HP fleet sized to between 3,000 and 6,000 run hours, this represents a heat pump peak demand of around 1 and 4GW.
- Significant penetration of heat pumps expected, as these enable a wide range of heat sources, particularly secondary or low-grade heat sources, to be tapped into.



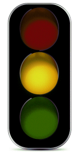


- Increasingly relevant from around 2030 as significant DH comes online.

- Counterfactual is CHP or HP only. Note that the role of gas CHP in DH provision will be increasingly limited by its environmental performance as the grid decarbonises.

1: *Research on district heating and local approaches to heat decarbonisation*, EE for CCC
2: Modelling will consider the CHP electrical generation being used by EHPs outside the DH system.

Substitution of process electric heating with gas / liquid fuel technology



Peak

Multi-vector system description

- Electricity for process heating can be substituted with gas heating or on-site diesel generation at times of high electrical demand.
- This would also allow for UPS, DUoS and Triad avoidance, so value to customer may be larger than system level peak shedding alone.

Issues addressed

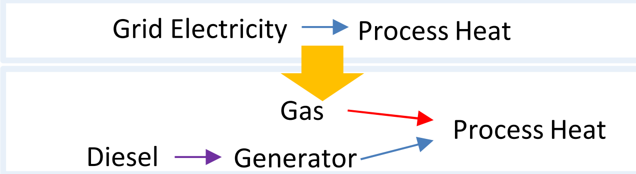
- Reduces investment required in electricity network reinforcement and capex / opex related to peak electricity generating capacity.
- Environmental case may be weak, particularly as grid decarbonises.

Current Situation

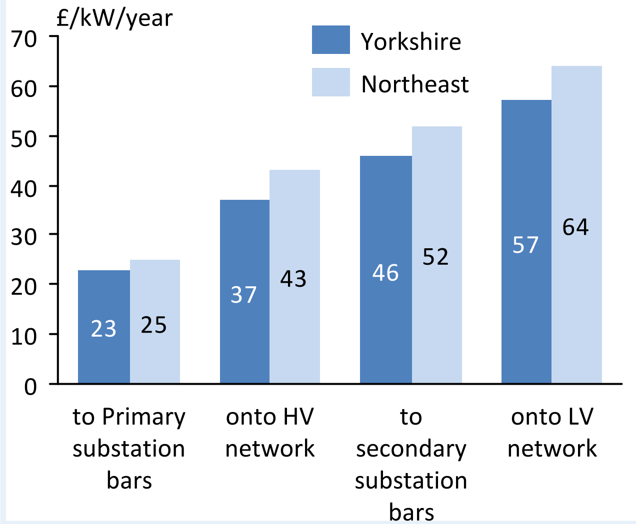
- Significant amounts of commercial and industrial peak load are already diesel shifted for DUoS and Triad avoidance.
- According to ECUK breakdown, all industries that use large amounts of high and low T process heat have a diverse range of fuel sources used for generation, so fuel switching seems possible across industries.

Materiality in UK energy system

- Around 3GW of electricity is used for process heating, though some of this may already be process managed.
- Long term marginal diesel generation costs are around £130/MW, based on UK National Grid capacity market auctions.
- Not all MW are created equal; taking 1 MW off the HV system is worth around 33% less than one taken off the LV system.



Amortised Grid Reinforcement Costs[1]

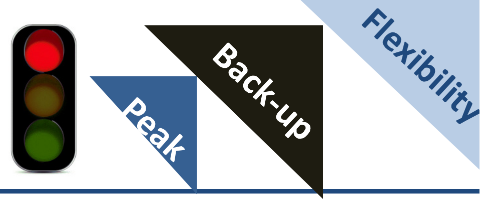


- Relevant where both LV and HV are subject to capacity constraints.

- Counterfactual is roughly unchanging industrial heating electrical demand, with turndown not considered (for the >hour long events in scope). DSM and storage would also need to be considered.

1: Data supplied by Northern Powergrid

Fuel cell vehicle feeding electricity to the home



Multi-vector system description

- > Hydrogen vehicles generate electricity in their fuel cells to power motors, at times of national or local peak demand this can be supplied to homes.
- > This allows H_2 to reduce stress on the electricity system, as long as production systems avoids high electrolyser loads at the same time (e.g. through storage).

Issues addressed

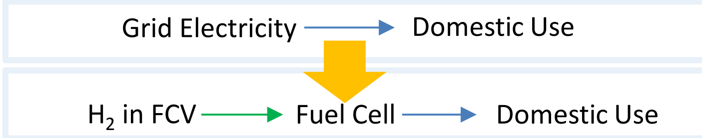
- > Limits peak demands imposed on the electricity system by domestic loads, particularly at the local level, and therefore lowers grid reinforcement and peak generation costs.

Current Situation

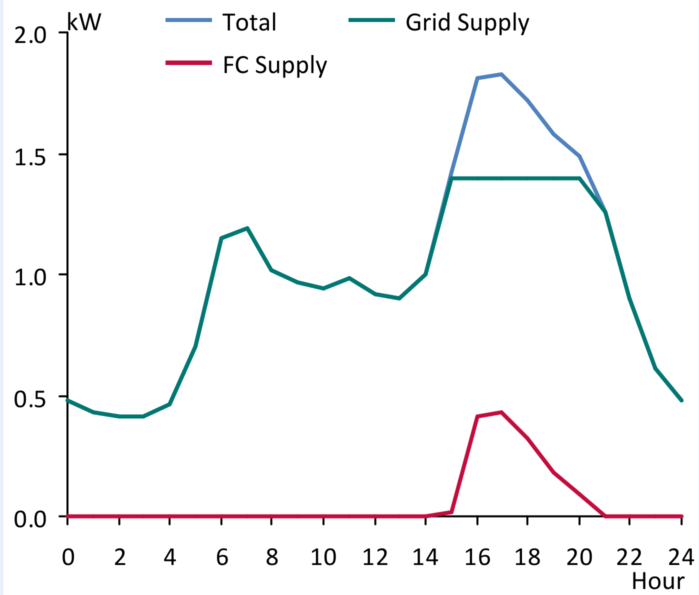
- > Few H_2 vehicles in domestic ownership, but significant growth expected with second generation vehicles launched in ~2020.

Materiality in UK energy system

- > By 2050, as many as 2.4m H_2 fuel cell vehicles could be on the road, based on EE ECCo modelling.
- > On-board H_2 storage could provide 75kWh of electrical output from 5kg H_2.
- > This interaction would require investment in a V2G system with inverters/power-conditioning to be installed at a home; the Toyota Mirai system is c. £3000 for 6kW output.
- > H_2 to grid electricity pathway relatively high cost (due to conversion loss and H_2 price), so this interaction is for back-up power rather than regular use.



Illustrative Domestic Diurnal Electrical Demand Profile



- > Relevant in high transport H_2 uptake scenario
- > Light vehicles are primary focus, as heavy vehicles are not parked for large fractions of a day.

- > Counterfactual is predominantly ICE fleet, or providing similar capabilities with BEVs or PHEVs

PHEV displacing electrical demand with petrol 1: Switching to liquid fuel-only operation during prolonged high electricity price period

Capacity

Flexibility

Multi-vector system description

> PHEVs could run on petrol or other fuel during a prolonged (~week long) nationwide generation shortage, likely during winter with low wind generation.

Issues addressed

> Limits daily or weekly total electrical demand on occasions where national renewable generation is low, reducing peak generation costs and allowing greater uptake of wind.

Current Situation

> NTS estimates around 60% of PHEV distance will be covered using battery, and 40% using petrol, though currently petrol dominates for incentive reasons. This is expected to change as drivers are exposed more fully to their energy costs.

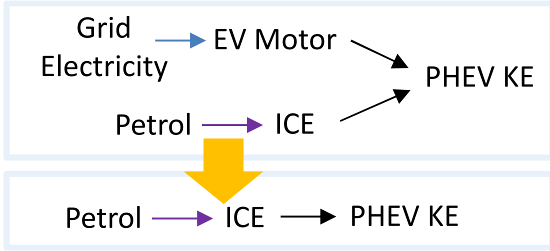
Materiality in UK energy system

> In a 50% EV sales by 2050 scenario in the EE ECCo model, there are around 9.4million PHEVs on the road in that year. This translates to a total battery capacity of 100 GWh and available V2G power of 10GW.

> Carbon emissions associated with driving 50 miles on petrol are around 8kg CO_2e. As the grid decarbonises the GHG emissions associated with charging the cars will fall, so that by 2050 running the UK fleet of PHEVs on petrol for a day is associated with net emissions of around 50,000 tonnes CO_2e.

> In this scenario, the petrol distribution system would experience increased demand of around 15 million litres, (around 10% the average daily offtake in 2013)

> Other energy streams could also be used; Mercedes have recently announced the GLC BEV will be powered by a 9kWh battery and a hydrogen fuel cell.



Carbon emissions associated with providing 10kWh Energy to a PHEV (kg CO_2e)

Year	Electric[1]	Petrol[2]
2015	5.8	8.2
2020	3.2	8.2
2030	1.4	8.2
2040	0.6	8.2
2050	0.4	8.2

> Relevant in a high PHEV uptake scenario.

> Counterfactual is electricity-system only solutions to peak loads or generation shortfalls

1: assumes 80% plug to wheel efficiency 2: assumes 30% efficiency combustion engine

PHEV displacing electrical demand with petrol 2: PHEVs Providing V2G

Peak

Capacity

Multi-vector system description

- Electrical vehicles charge at points at or near the home. At times of high electrical system load, the flow of energy can be reversed, providing a distributed power source. The cars can then be run as usual on petrol, rather than having to conserve or re-charge overnight for morning use. In particularly severe conditions, the car can serve as a generator, using the kinetic energy lost during braking to charge the batteries and supplying this to the grid.

Issues addressed

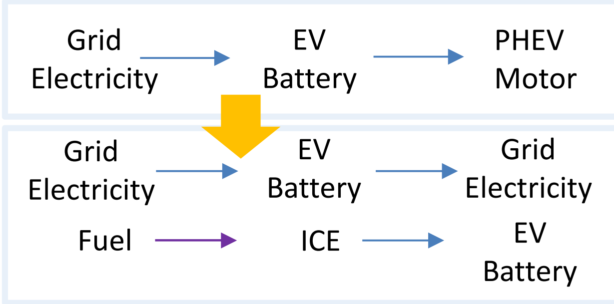
- Limits peak demands imposed on the electricity system at the LV level.
- V2G also provides a source of DSM, so that the system costs would not need to be met by the multi-vector interaction value alone.

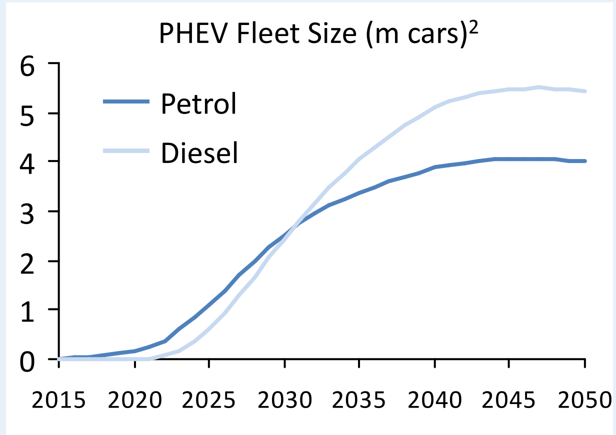
Current Situation

- Nissan currently conducting V2G trials with ENEL using an off-vehicle DC charger and inverter. Focus so far is on BEVs rather than PHEVs

Materiality in UK energy system

- In a 50% EV sales by 2050 scenario, there are 9.4 million PHEVs on road, according to a bullish EE ECCo model scenario.
- This translates to a total battery capacity of 60 GWh and available V2G power of 10GW, though only a fraction may be connected to grid at times of peak electrical demand. Only a fraction of the fleet are likely to be charged and fuelled at any time
- In extremis, ICE could act as a generator; the KE lost to braking on a 50 mile petrol-powered drive of around 1kWh[1] could charge batteries and be supplied to the grid.



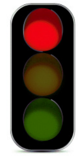


- Relevant in a relatively high PHEV scenario for significant periods of low generation.

- Counterfactual is phasing out of petrol infrastructure and the associated grid and generation reinforcement, as in previous scenario, with V2G used for DSM.

1. Assumes 30 mph driving speed, 1 dead stop every 2 miles.
2. Source: EE ECCo model.

Range extender H2FC vehicle – H_2 used to recharge batteries at times of electrical system stress



Flexibility

Multi-vector system description

- > FC BEVs can use stored hydrogen to power their motors and extend their battery-only range. Such vehicles, particularly those in fleets which are centrally refuelled, could use the hydrogen network (rather than the grid) to charge their batteries overnight where such depots are in areas of grid constraint, and run independently of the grid for extended periods, or indeed indefinitely.

Issues addressed

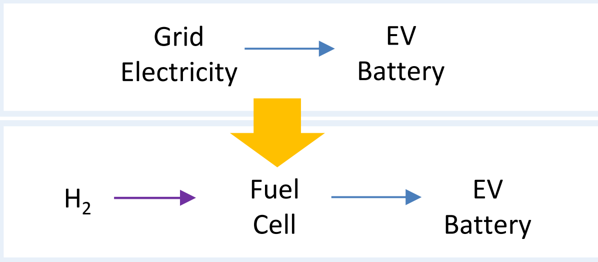
- > Limits local peak demands imposed on the electricity system.
- > Reduces investment required in electricity network reinforcement for local, energy intensive facilities.
- > If H_2 is electrolysed, the round trip efficiency is around 25% of grid charging, so constraints would need to be significant.

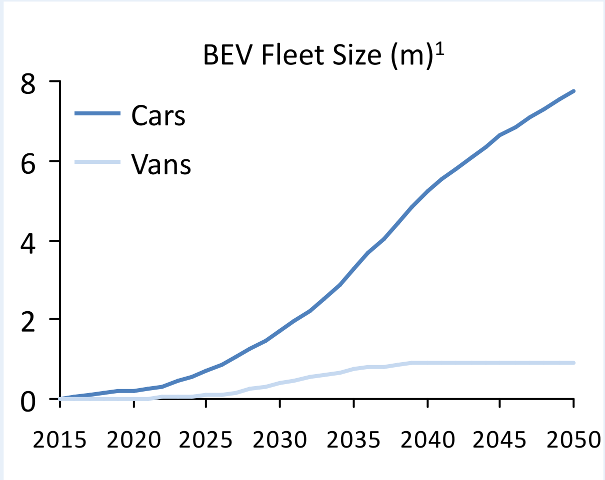
Current Situation

- > French postal service conducted small scale trial of range extended vans in 2014. The Chevrolet Bolt and BMW i3 are cars looking at this technology.

Materiality in UK energy system

- > Around 7.7m BE cars and 0.9m BE vans are on the road in 2050 in the EE ECCo model high uptake scenario. Assuming 25% of the vans and 10% of cars are fuel-cell charged, this represents around 30GWh of daily demand taken off the electrical system.
- > The environmental impact of this solution will depend on the hydrogen source. Using electrolysis, charging this entire fleet would account for net emissions of around 3,000 tonnes CO_2 compared to grid charging even at 2050 emissions intensity.



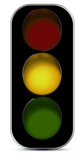


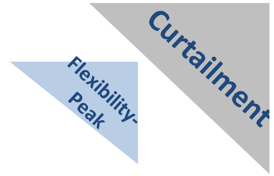
- > Relevant in high FC BEV high H_2 future, particularly for vans, company cars or other fleets which are charged at a central depot, typically overnight.

- > Counterfactual involves of BEV fleet without significant range extenders and/or limited H_2 network.

1. Source: EE ECCo model

RES to Gas 1: RES-to-Hydrogen





Multi-vector system description

> RES plants connected to the transmission/distribution network generate electricity which is exported to the grid or converted to hydrogen at times of generation surplus or network constraints. The produced hydrogen can be compressed and stored or blended into the existing natural gas grid.

> Stored H_2 can be re-electrified (at 20-30% round trip efficiency) , used as fuel for FCVs or used in the industry.

Issues addressed

> Limits curtailment of RES in cases of oversupply or due to network constraints, deferring network reinforcement.

> Enables the system to respond to price signals or provide balancing services to TSO at times of energy imbalance (e.g. reduce export to the network).

> Enables the system to reduce peak demand by increasing local generation.

Current status

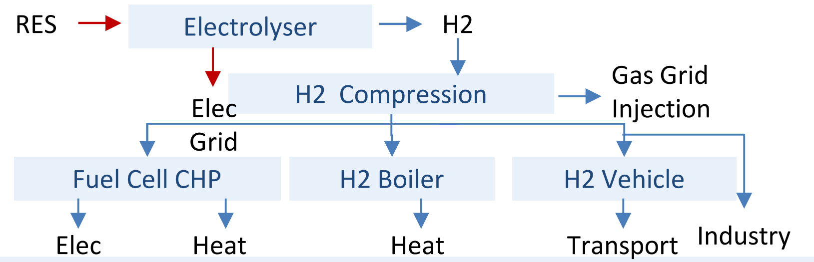
> Existing power-to-H_2 project in the UK: Wind Hydrogen station in Rotherham with on-site hydrogen generation from wind, M1 wind hydrogen station in Yorkshire. Hydrogen network project: H21 Leeds Citygate.

> There are numerous power-to-gas demonstration projects in Germany e.g. Thuga P2G.

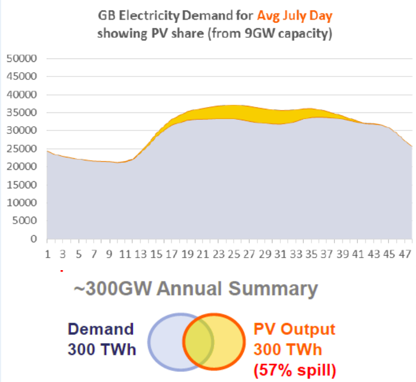
> Volume share of H_2 in the natural gas system is currently capped at 2%.

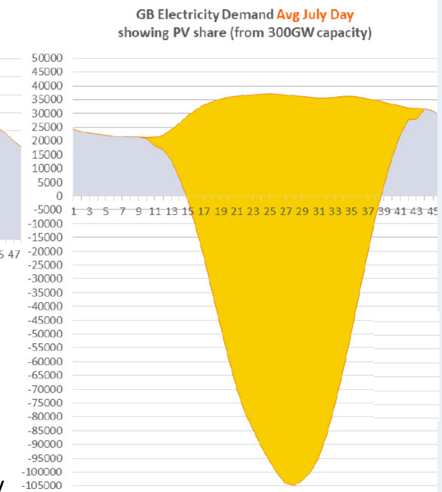
Materiality in UK energy system

> A UCL study[1] of the long term UK energy system assuming 27GW of wind (72GWh produced) in 2050 and taking into account the local and temporal characteristics of RES showed most of the wind deployment occurring on the coasts and North and being heavily curtailed at approx. 45%.



PV Generation against national electricity demand in 2015 and 2050[2]





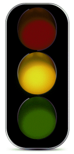
ETI PV capacity scenarios (2015: 9GW, future: 300GW) vs GB electricity demand for average July day estimate a 57% "spill".

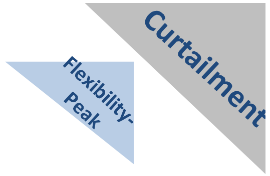
> Counterfactual scenario for network-related curtailment: Network reinforcement or electricity storage

> Counterfactual scenario for generation surplus-related curtailment: Curtailment continues or electricity storage is installed.

1. *Spatially & temporally explicit energy system modelling to support the transition to a low carbon energy infrastructure*, UCL
2. *A perspective on whole systems energy modelling,* ETI

RES to Gas 2: RES-to-CH4





Multi-vector system description

- RES plants connected to the network generate electricity which is either exported to the grid or converted to bio-methane (via electrolysis and subsequent methanation) at times of generation surplus, network constraints or price signals
- The produced biomethane is injected and stored in the natural gas grid and used for industry, heat, transportation, power (no limit on the mixture)

Issues addressed

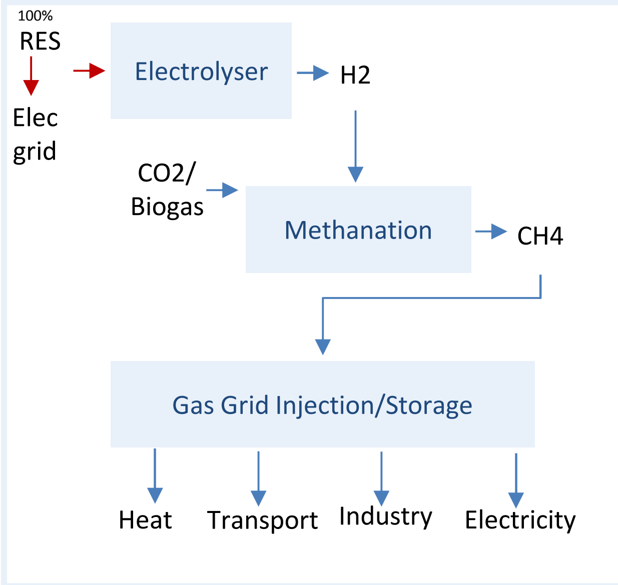
- Limits curtailment of RES in cases of oversupply or at periods with network constraints, deferring network reinforcement
- Enables the system to be respond to price signals or provide balancing services to TSO at times of energy imbalance (reduce export to the network)
- Enables the system to reduce network peak demand by increasing local generation
- Provides a means for seasonal storage and the transmission of excess of energy (in the form of gas) over long distances

Current status

- Biomethane is already injected into natural gas systems and the last few years more pilot and demonstration projects of Power-to-Gas CH4 were launched worldwide e.g. E-Gas Project Audi Germany.

Materiality in UK energy system

- £90m were paid to wind farms to curtail their energy in 2015
- UCL's study[2] showed a scenario of heavy curtailment (~45%) of wind in 2050.
- Excess wind generation in Scotland can be stored and transmitted as gas to the south to meet the local high demand.



- Low efficiencies for power-to-power solutions at around 20-30%
- Methanating the electrolysed hydrogen reduces the overall process efficiency from 73% to 58%[3].

- Counterfactual scenario for network-related curtailment: Network reinforcement or electricity storage.
- Counterfactual scenario for generation surplus-related curtailment: Curtailment continues or electricity storage is installed.

1. *The potential of Power to Gas*, ENEA Consulting 2. *Spatially & temporally explicit energy system modelling to support the transition to a low carbon energy infrastructure*, UCL 3. *Technology Roadmap, Hydrogen and Fuel Cells*, IEA

RES to heat store or DH

Curtailment

Flexibility

Multi-vector system description

> Plants connected to the transmission/distribution network generate electricity which is exported to the grid or used for heat storage at times of generation surplus or network constraints. This solution allows the possibility to flex between electricity and DH based on electricity prices and heat demand.

Issues addressed

> Allows excess RES energy to be collected as heat for later use, hours, days or months later (seasonal thermal energy storage) at building, district, town or regional scale.

> Limits curtailment of RES at periods of low demand or network constraints, and helps the deferral of reinforcement for the connection of RES.

> Provides a means for seasonal storage of electricity and load shifting while enabling the uptake of large-scale heat pumps, and could provide a heating solution for off gas grid locations.

Current status

> Heat networks for residential use currently supply less than 1% of homes[1].

> Examples of current district heating systems include Pimlico District heating and Thameswey Central Milton Keynes, typically based on gas CHP[2].

Materiality in UK energy system

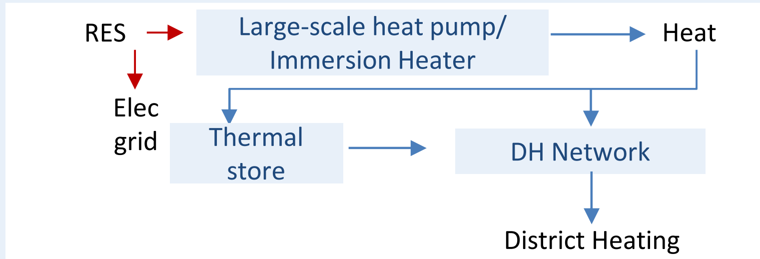
> £90m were paid to wind farms to curtail their energy in 2015.

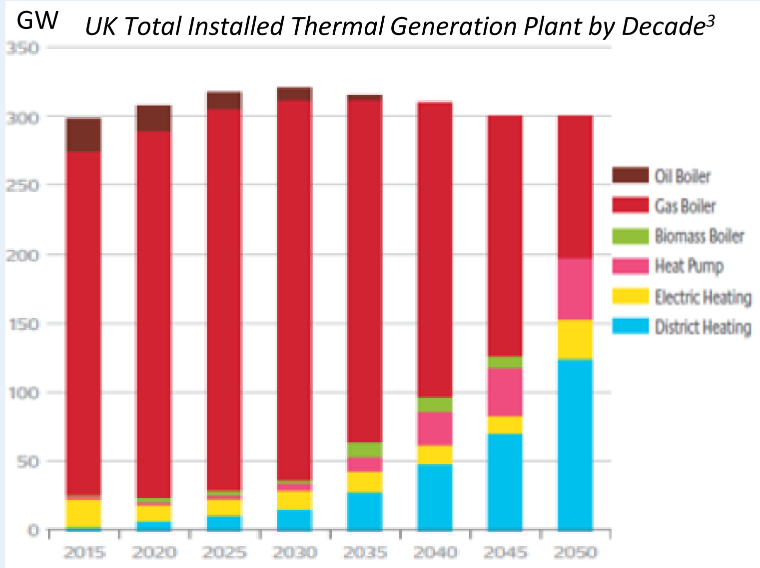
> UCL's study showed a scenario of heavy curtailment (~45%) of wind in 2050.

> 80TWh of heating demand could be met by DH by 2050[1].

> ~18% of homes (4million properties) are not connected to the NG gas network.

> In ETI's clockwork scenario, ~40% of space heat capacity (120GW) and 36% of space heat generated (140TWh) is based on DH in 2050[3].



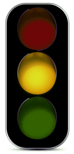


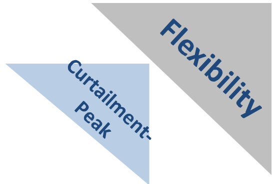
> Counterfactual scenario for network-related curtailment: Network reinforcement or electricity storage

> Counterfactual scenario for generation surplus-related curtailment: Curtailment continues or electricity storage is installed

1. *Future Energy Scenarios 2015*, National Grid. 2. *Thermal storage District Heating systems Report,* Tyndall Centre
3. Source ETI, *Patchwork-Clockwork scenarios 2050 and Bioenergy*

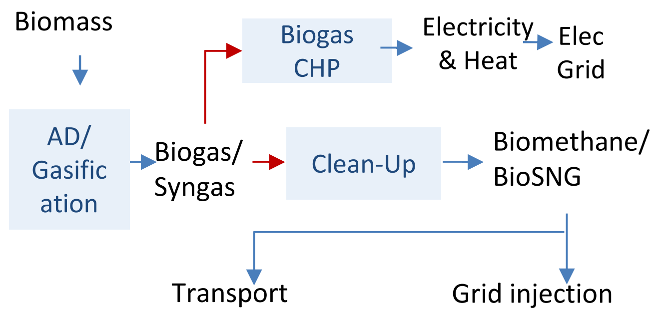
Anaerobic digestion/Gasification to CHP or gas grid injection





Multi-vector system description

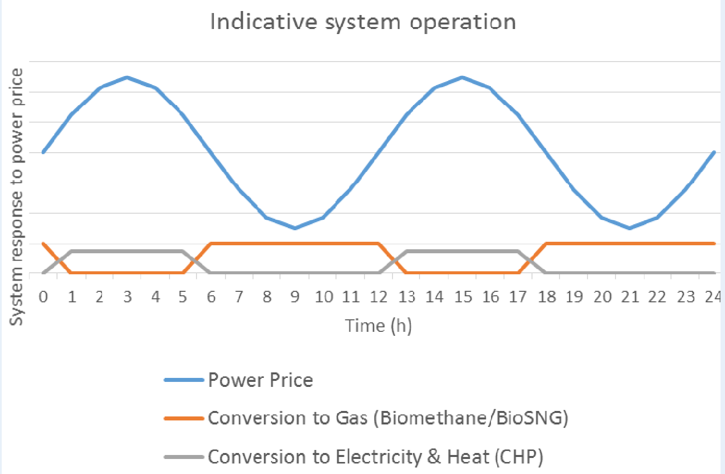
- Biomass feedstock (e.g. food waste, energy crops, agricultural residues, industrial waste and co-products) is converted to either biogas (via AD) or syngas (via gasification) and then used either as a fuel for CHP plants exporting electricity to the grid or upgraded to biomethane/BioSNG and injected to the natural gas grid.
- Switching to electricity or gas mainly triggered by electricity/gas price signals
- Electricity can be chosen over gas production to meet network peak demand.
- The shift to the gas vector can be made at times of network constraints to avoid RES curtailment.



Red arrows indicate the key operational decision point

Issues addressed

- Provides a way to flex between gas and electricity based on price signals representing the availability of these resources.
- Provides a way of meeting peak demand by increasing local generation and thereby reducing demand seen by upstream network assets and deferring network reinforcement.
- Limits curtailment of electricity generated at periods with network constraints, deferring network reinforcement.



Current status

- AD is proven and mature with a well developed supply chain and investment community. Used in farming & agriculture for reducing expenditure on artificial fertilisers and CHP.
- By the end of 2015, the established AD biomethane facilities had the capacity to inject 2TWh/annum into the gas network, equivalent to 155,000 homes [1].
- The first BioSNG demonstration plant in the UK is under construction.

- Counterfactual is the export of electricity produced with the CHP to the grid facing the risk of curtailment at times of network constraints and revenues being solely dependent on electricity prices.

Materiality in UK energy system

- DECC Bioenergy Strategy 2050: about 12% of 2050 UK total primary energy demand could be met by indigenous UK biomass.
- Bioenergy can be deployed to meet approx. 10% (130 TWh) of 2050 energy demand[2]

1. *The future of gas-Supply of renewable gas,* National Grid
2. *Insights report into the future of UK Bioenergy Sector*, ETI

H2 from SMR or electrolysis into dedicated H2 grid

Back-up
Curtailment
Flexibility

Multi-vector system description

- The majority of hydrogen is produced via SMR (with/without CCS) using natural gas from the gas grid via electrolysis but can be also produced using the excess of RES that could otherwise be curtailed
- Switching to electrolysis could be triggered by the excess of RES generation or electricity/gas price signals
- Hydrogen could be injected to a dedicated hydrogen network

Issues addressed

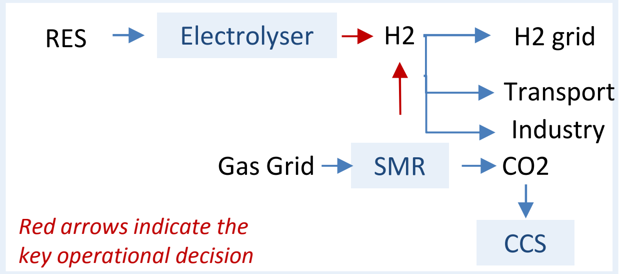
- Provides a cheap (and potentially clean) back-up source of hydrogen feeding a future dedicated hydrogen network as well the industry and transport directly at times of gas shortage or high natural gas prices
- Provides a way to utilise RES electricity generation for the production of clean hydrogen whenever possible
- Provides a way to flex between gas and electricity based on price signals indicating the availability of these resources

Current status

- The most common approach for producing hydrogen is Steam Methane Reforming (SMR) without CCS. Combined with carbon capture and storage would be equivalent to other renewable sources.

Materiality in UK energy system

- Around 50% (around 20 million FCVs) of light duty stock in UK are hydrogen fuelled under the High H_2 deployment scenario (*4th Carbon Budget*, CCC; 2050 Pathways, DECC; *Transport Infrastructure Needs Assessment*, Carbon Trust)
- NG envisages that heating with hydrogen transported via a dedicated H2 polyethylene system will become more relevant post 2050 (*FES 2016*, National Grid).



- In the early years of hydrogen transport scenarios much of the hydrogen will come from SMR without CCS whilst in the long term the dominating methods for producing hydrogen will be water electrolysis and low carbon syngas (Carbon Trust and Element Energy analysis)

- Efficiency of electrolyser depends on technology: 65-82% HHV for Alkaline, 65-78% for PEM,SO (R&D) 65-90% (IEA, “Technology Roadmap, Hydrogen and Fuel Cells”)
- Efficiency of SMR for large scale applications is 70-85%

- Counterfactual is the production of hydrogen from SMR using gas without utilising the excess of RES in the electricity grid and the additional flexibility to respond to gas prices.

H2 from pre-combustion CCS to Power/Transport/Heat

Flexibility

Multi-vector system description

- Pre-combustion capture involves gasification and partial oxidisation of a fuel (e.g. coal) to produce CO_2 and H_2 which are separated. CO_2 is captured and stored.
- Produced hydrogen is used to generate electricity from a fuel cell plant (could be CHP) or a modified gas turbine.
- Hydrogen can alternatively be used for heating with hydrogen boilers or to fuel hydrogen vehicles.

Issues addressed

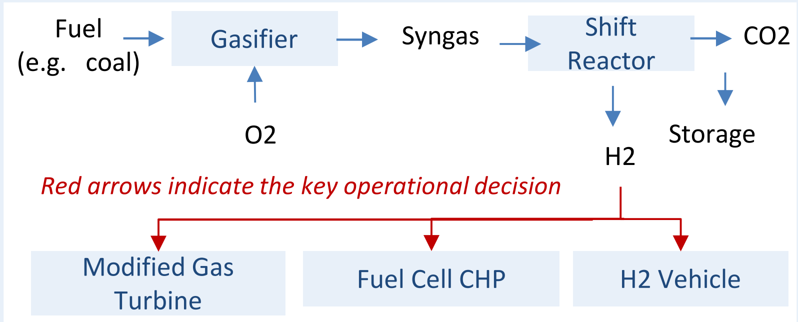
- Multiples fuels can be used to produce hydrogen with this method.
- Hydrogen can be utilised to meet power, heat and transport needs.
- The option of using the produced hydrogen for electricity generation provides flexibility to the electricity system and allows it to generate electricity at times of high electricity prices.

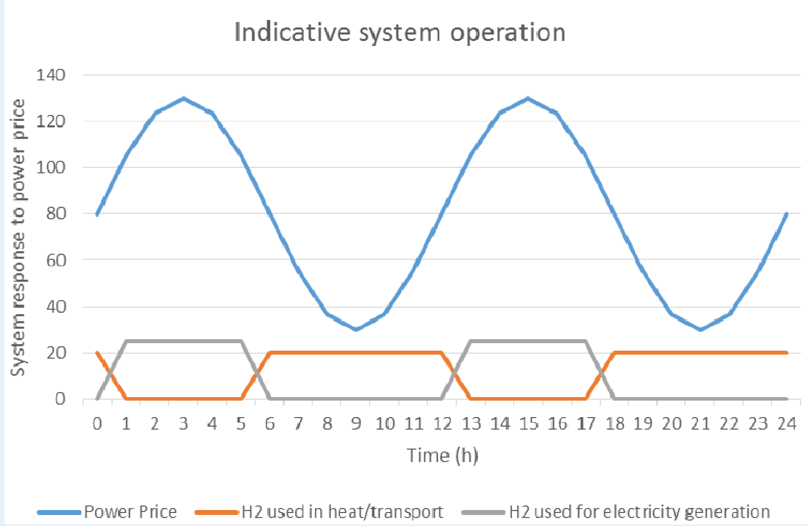
Current status

- When gas turbines are able to burn high shares of hydrogen, power generation based on fossil fuels and pre-combustion CCS could be promoted .
- CCS is expensive to implement and needs infrastructure external to the power stations to function, therefore is considered economical in high-density clusters of industrial activity and near a carbon sink point like the North East of England and Scotland.

Materiality in UK energy system

- In November 2015, UK government dropped a grant given for CCS (Peterhead power station and White Rose) with other companies abandoning plans to introduce CCS.
- National Grid considers the production of hydrogen with CCS to be relevant post 2050[1].





- Efficiency of hydrogen generation and conversion via coal CCS is currently approx. 56% increasing to 60% in 2050[2].

- Counterfactual is produced hydrogen is used for a single energy vector (e.g. hydrogen vehicles) without any additional flexibility.

1. *The future of Gas - Supply of renewable gas,* National Grid
2. *Technology Roadmap, Hydrogen and Fuel Cells,* IEA

Following the identification of the case studies above, they have been filtered and prioritised on the following bases

Long-list of interactions

WP1

Filtering of interactions classified as low material impact based on WP1 analysis

Initial shortlist validated by steering group

WP2

Confirmation of short list based on more detailed WP2 analysis using the following criteria

The extent to which the interaction solves an energy system issue / constraint

Materiality on an energy / power demand basis

Spread of scale / position in the energy system

Timescale it becomes relevant

Previous work on the topic

Short-list of vector interactions distributed along the spectrums of type, scale, timing and operational complexity

Note: WP2 was originally expected to involve a further reduction in the number of cases to take forward in the analysis. Since the filtered list is of 6 cases at the end of WP1, WP2 will increase the robustness of the assessment criteria for the shortlist, but will primarily focus on definition of system boundaries, demand profiles etc. in preparation for the WP3 analysis.

Matrix of Multi-Vector interactions vs Services Provided (1)

Technology/Service	Peak avoidance	Flexibility	Generation capacity constraint	Generation curtailment	Back-up	RAG Rating
Heat pumps with peak load boilers	**X**	X			X	Green
CHP combined with a heat pump in a single building	**X**	X	X			Red
Gas CHP and electrical heat pumps serving a district heating system			**X**			Yellow
Substitution of electric process heating with gas / liquid fuel technology	**X**	X			X	Yellow
Fuel cell vehicle feeding electricity to the home	X	**X**			X	Red
PHEV displacing electrical demand with petrol 1 : Switching to liq. fuel only running during high electricity price period	X		**X**			Yellow
PHEV displacing electrical demand with petrol 2: V2G		X	**X**			Yellow
Range extender H2FC vehicle – H2 to recharge batteries at times of electrical system stress	X	**X**	X			Yellow

X –indicates primary service provided by multi-vector interaction X – indicates secondary service

Peak avoidance – *Mainly related to the electricity network. Electricity demand is substituted by another vector or local generation increases at peak times to reduce demand seen by upstream network assets*
Flexibility – *System provides ability to flex between vectors due to a range of price signals or helping SO deal with (close to delivery) fluctuations in the demand and supply balance (balancing services)*
Generation capacity constraint – *Switch from one vector to another due constrained generation capacity*
Generation curtailment – *Curtailment of a generating technology due to network constraint or (longer-term) generation surplus*
Back-up – *Use of an alternative energy vector to back-up a primary source*

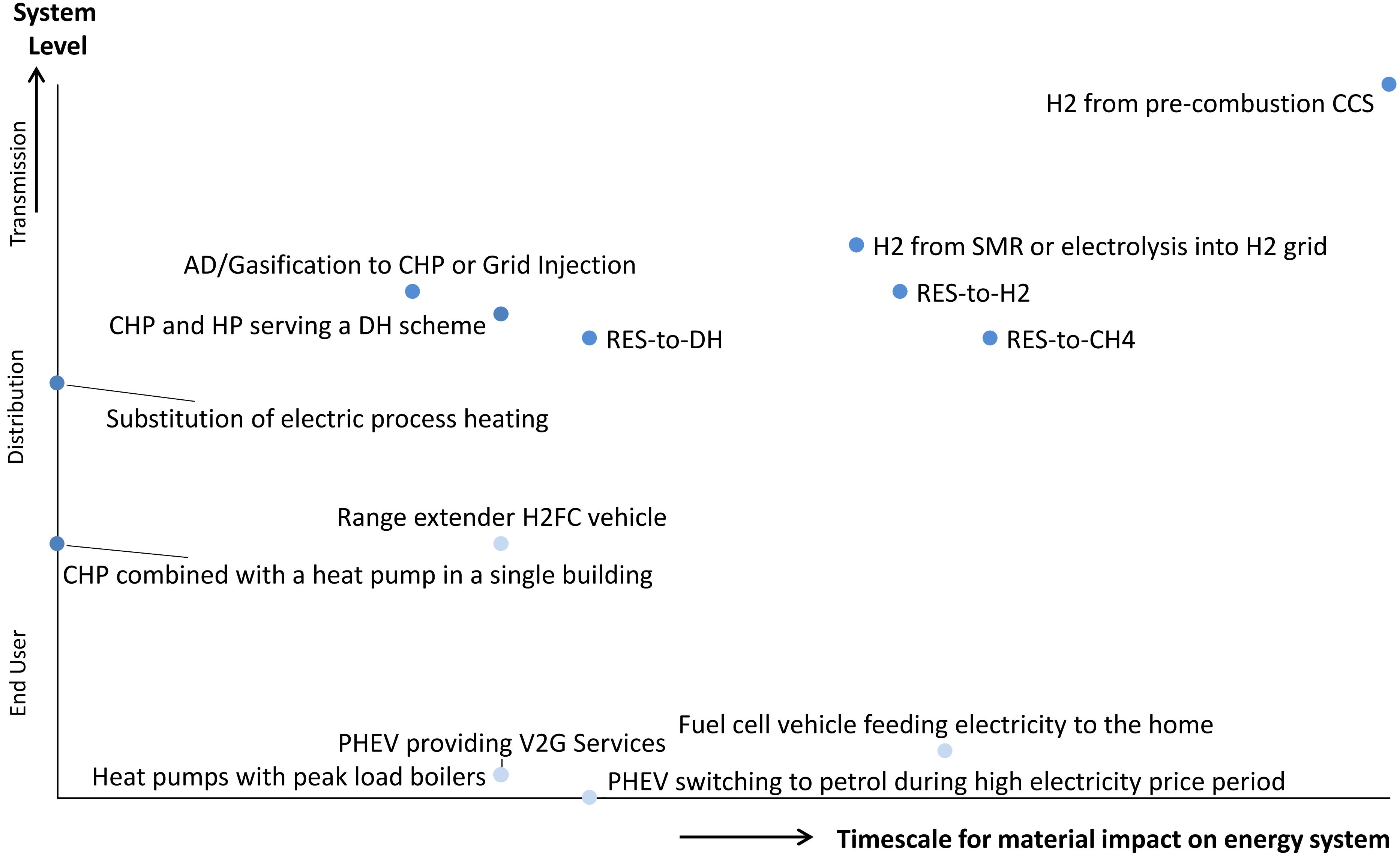
Matrix of Multi-Vector interactions vs Services Provided (2)

Technology/Service	Peak avoidance	Flexibility	Generation capacity constraint	Generation curtailment	Back-up	RAG Rating
RES-to-H2		X		**X**		
RES-to-CH4		X		**X**		
RES-to-DH		X		**X**		
RES-to-Virtual DH		**X**				
AD/Gasification to CHP or Grid Injection	X	**X**		X		
H2 from SMR or electrolysis into dedicated H2 grid		**X**		X	X	
H2 from pre-combustion CCS to power/transport/heat		**X**				

X –indicates primary service provided by multi-vector interaction X – indicates secondary service

Peak avoidance – *Mainly related to the electricity network. Electricity demand is substituted by another vector or local generation increases at peak times to reduce demand seen by upstream network assets*
Flexibility – *System provides ability to flex between vectors due to a range of price signals or helping SO deal with (close to delivery) fluctuations in the demand and supply balance (balancing services)*
Generation capacity constraint – *Switch from one vector to another due constrained generation capacity*
Generation curtailment – *Curtailment of a generating technology due to network constraint or (longer-term) generation surplus*
Back-up – *Use of an alternative energy vector to back-up a primary source*

Distribution of interactions across dimensions of scale and timescales of likely relevance



Filtering interactions with a low future impact on the UK energy system yields the following proposed Shortlist for Work Package 2

It is proposed that the following scenarios are taken forward for detailed analysis

1. Domestic scale heat pumps and peak gas boilers.
2. Gas CHP and Heat Pumps to supply district heating and individual building heating loads

   2a) CHP and heat pumps operating to supply heat to district heating

   2b) CHP supplying district heating, with co-generated electricity used to power individual dwelling heat pumps
3. PHEV switching fuel demand from electricity to petrol or diesel.
4. RES to H2/RES to CH4
5. RES to DH and "virtual" DH networks
6. Anaerobic Digestion/Gasification to CHP or grid injection

List or shortlisted multi-vector interactions to be used in Work Package 2 was agreed by the project steering group during teleconference on Monday July 4th

Cases of interest have been identified; they will now be filtered into a set of detailed case studies based on their potential to benefit the system

T1 Mapping vector interactions

- *Multiple vectors serving a single energy demand, e.g.*
  - *Gas and electricity meeting peak heat demands*
  - *Gas generation balancing / back-up for intermittent renewables*
- *Conversion between vectors for transport of energy (potentially with re-conversion)*
  - *Power-to-gas to avoid transmission constraints*
  - *RES electricity to district heat system*
- *One vector used to generate another vector, while also meeting other demands*
- *Conversion from one vector to multiple vectors, e.g. CHP*

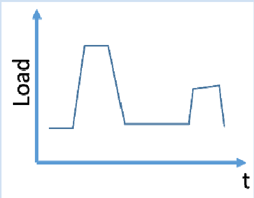
T2 Case identification

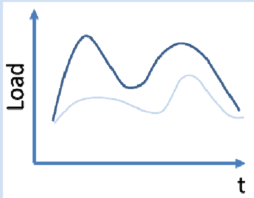
- The mapping task (T1) will seek to be exhaustive; in this task we filter down and focus on cases that deliver benefits to the system, such as:
  - Increasing capacity for RES
  - Managing increased adoption of low carbon technologies
  - Decarbonising heat
  - Integrating low carbon energy into transport demands
- Identify cases that are genuinely distinct from the 'conventional' counterfactual
- Define system configurations for each case
- Define the boundary for the analysis of each case – seek to ensure the analysis captures a high fraction of the cost difference between multi-vector and counterfactual configurations
- Qualitative assessment of cost impacts outside the defined boundary

We will then combine quantitative analysis of multi-vector configurations and a consultative approach to understanding operational implications

T3a: Network Analysis

- Develop demand profiles and assess sizing of technologies / networks in multi-vector & baseline cases





- Network modelling / simulation to assess key operating parameters
- Use modelling tools – Simone (gas), Sincal (electricity), in-house DH models etc. – and team design / analysis experience

- Capacity and operational parameters pass to T4 to underpin costing and benefit analysis

T3b: Operational / engineering analysis

- Detailed assessment of the operational implications of the multi-vector operating regimes
- Draft analytical framework:

Dimensions to assess	Identify issues	Severity of impact	Potential solutions	Changes / innovation required
Technical issues				
Management / coordination				
Commercial / market				
Regulatory				

Assess operational implications of each multi-vector mode

- Operational and engineering analysis will draw on:
  - experience of the Core & SME teams
  - Additional consultation with industry experts

Appendix

Acronyms

AD – Anaerobic Digestion

BEV- Battery Electric Vehicle

CCC - Committee for Climate Change

CCS – Carbon Capture and Storage

CHP – Combined Heat and Power

CO_2e - Carbon Dioxide equivalent

DC – Direct current

DECC - Department of Energy and Climate Change

DfT - Department for Transport

DH – District Heat

DNO/DSO – Distribution network operator/ Distribution system operator

DSM – Demand Side Management

DUoS – Distributed Use of Service

EE - Element Energy

EHP – Electric Heat Pump

ETI - Energy Technologies Institute

EV – Electric Vehicle

FCV – Fuel Cell Vehicle

HGV - Heavy Goods Vehicle

HP – Heat Pump

HV – High voltage

HW – Hot water

ICE – Internal Combustion Engine

KE – Kinetic energy

LV – Low voltage

P2G – Power to Gas

PHEV – Plug-in Hybrid Electric Vehicle

RES – Renewable Energy Source

Repex – Replacement expenditure

RfP - Request for Proposal

SGF – Smart Grid Forum

SMR – Steam Methane Reformer

UCL - University College London

V2G – Vehicle to Grid

Summary of Energy Flow Diagram